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# RESEARCH MEMORANDUM

## PRELIMINARY INVESTIGATION OF A CERAMIC LINING FOR A COMBUSTION CHAMBER FOR GAS-TURBINE USE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
April 12, 1948

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# PRELIMINARY INVESTIGATION OF A CERAMIC LINING FOR A COMBUSTION CHAMBER FOR GAS-TURBINE USE

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## SUMMARY

A ceramic-lined test chamber was operated at fuel-air ratios up to 0.050. Thermal-shock evaluation indicated that a ceramic lining which expands after firing would crack but would not fall apart during operation. Refractoriness of the ceramic lining and the resistance to mechanical shock were adequate. In general, shell temperature reductions of approximately 400° F were effected by the use of this lining at fuel-air ratios of 0.016 and 0.050. The mechanism of failure of the ceramic lining was induced by sudden heating and cooling during operation.

## INTRODUCTION

Analysis of present-day combustion cycles in aircraft gas turbines indicates a need for increased operating temperatures to permit increased efficiency of operation. The high-temperature alloys currently in use limit operating temperatures of materials to approximately 1600° F and show little promise of permitting any immediate substantial increase in operating temperature. The high melting points, the low thermal conductivities, and the low potential cost of available ceramic materials prompt the consideration of such materials for application in gas-turbine parts.

All combustion chambers of current gas turbines for aircraft use consist of an outer shell and an inner liner. The purpose of the inner liner is to permit combustion to occur at a favorable fuel-air ratio by shielding the flame from the bulk of the air. Holes or slots in the inner liner permit inlet air to mix with the products of combustion some distance from the point of initial combustion.

As a preliminary procedure to this investigation, a number of failed combustion-chamber liners obtained from service turbines and from experimental laboratory setups was examined. It was obvious that some attribute of combustion, such as stress, temperature, gaseous atmosphere, or a combination of these factors, was responsible for failure.

A number of experiments was consequently conducted with liners consisting of ceramic materials. These liners invariably cracked during operation due to thermal stresses set up within the liner. It appeared necessary either to minimize thermal stresses by constructing a liner of small segments, in any one of which no large thermal gradient could appear because of the small size of the segment, or to increase resistance to thermal-stress failure by reinforcing the ceramic. A reinforced ceramic shell was therefore examined at the NACA Cleveland laboratory to determine its suitability for combustion use inasmuch as a liner constructed of small segments was under investigation elsewhere.

The simplest method of reinforcing the ceramic was to cast it inside a metal shell; such a shell was therefore constructed and sent to the National Bureau of Standards, where a ceramic lining was cast into position. It was found that, for purposes of evaluating the ceramic under combustion conditions, no inner lining was required. The combustor was operated in a stationary test unit with AN-F-23a gasoline as fuel.

The purpose of this paper is to report only the behavior and the mechanism of failure of the ceramic lining under combustion and to mention the possibilities of operation of such a combustor from the point of view of the limiting fuel-air ratios at which combustion may be maintained without damage to the liner.

## APPARATUS AND SPECIMEN

The test chamber was circular in section with a tapered conical section of reduced area at each end. The length of the chamber was $28\frac{1}{2}$ inches, the maximum outside diameter was $12\frac{1}{2}$ inches (fig. 1), and the minimum inside diameter was $5\frac{1}{4}$ inches; the over-all weight of the housing and the ceramic lining was 54 pounds.

The test unit consisted of a static burner setup, as shown in figures 2 and 3. Combustion air was passed through an inlet duct into which fuel was sprayed. Ignition was accomplished by a spark plug. The inner liner upstream of the test chamber served as a flame holder and as a means of providing turbulence (fig. 4). The test chamber was equipped with thermocouples (figs. 1 and 2),

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past which the combustion gas flowed. Water sprays cooled the hot gas in the exhaust ducting. Water was injected into the gas stream in the direction of the gas flow by means of eight spray nozzles. Four nozzles were placed immediately downstream of the thermocouple section and four more about 10 feet downstream of the thermocouple section (fig. 3).

The reference thermocouple section, in which two thermocouples were mounted in tandem, was installed directly downstream of the test chamber. One installation consisted of a quadruple-shielded alumel-chromel thermocouple. The second installation consisted of a platinum - platinum-rhodium thermocouple element mounted inside a sealed, gas-impervious aluminum-oxide tube that extended outside the duct.

Eight alumel-chromel thermocouples were spot-welded on the outside surface of the test chamber, four at the maximum diameter and two on each of the tapered sections (fig. 1). Twelve alumel-chromel thermocouples were mounted in the ceramic lining at points as nearly alined as possible with the thermocouples spot-welded on the outer shell. Eight of these thermocouples were mounted in pairs every 90° of circumference in the section of maximum diameter and the other four were installed in the tapered outlet section, one at each 90° of circumference (fig. 1). The depth of the thermocouples in the ceramic varied from 3/16 to 5/16 inch from the outside surface.

Temperatures measured by the alumel-chromel thermocouples were indicated by a self-balancing potentiometer. Readings of the platinum - platinum-rhodium thermocouple were indicated by a manually operated slide-wire potentiometer. Rates of fuel flow and combustion-air flow were measured by a rotameter and by a thin-plate orifice, respectively. For all tests, combustion air was supplied at a nominal gage pressure of 30 pounds per square inch. During all tests, the exhaust trench was evacuated to a pressure corresponding to 6 inches of water below atmospheric pressure. The fuel used in all tests was AN-F-23a gasoline.

The outer shell of the test chamber was fabricated from 1/16-inch thick Inconel sheet. The shell was lined by the National Bureau of Standards with a selected ceramic having a composition designated A-329. This composition varied from the ceramic coatings as presented in reference 1 in that the mixture was hydraulic setting and therefore could be cast into molds to give a concrete-hard mass after a curing period of approximately 24 hours.

The composition of this A-329 ceramic liner material was as follows:

| Ingredient | Parts by weight |
|---|---|
| Lumnite cement[1] | 50 |
| Calcined aluminum oxide[2] | 25 |
| Fused magnesium oxide[3] | 25 |
| Lepidolite[4] | 5 |
| Water | 27.5 |

[1]Calcium-aluminate type hydraulic cement from the Atlas Lumnite Cement Co.

[2]T-60 grade, sized to pass 60-mesh sieve, from Aluminum Ore Co.

[3]Sized to pass 30-mesh sieve from General Electric Co.

[4]Sized to pass 100-mesh sieve.

These ingredients were first dry-mixed after which the water was added and mixed into the dry batch. Previous to this mixing, the Inconel chamber was disconnected at the flange between the center and front section to give two parts. A plaster-of-Paris core was then turned for each part to give approximately a 3/8-inch clearance with the chamber wall. Shellacked paper was next placed over the core and a light coating of grease applied over the paper.

In casting the ceramic liner, the core was first centered in the chamber part after which it was placed on the platform of a Jeffrey-Traylor electro-vibrator having a vibration frequency of 3600 cycles per minute. The wet batch was then slowly poured into the space between the core and the wall until level full. After pouring, the parts were set aside for 24 hours to cure and harden after which the cores were removed.

Firing was done at 2300° F for 30 minutes in an unmuffled furnace but with the flame adjusted to give a slightly reducing condition. In spite of this precaution, heavy scale formed on the Inconel but it was, for the most part, tightly adherent.

After the firing operation, which caused a small permanent expansion in the ceramic, the ends were smoothed by grinding and the two parts again bolted together. A final treatment consisted in brushing a thin layer of an air-setting refractory mortar over the entire inner surface of the liner. This treatment sealed the crack that was present where the two sections were joined together and also gave a harder, more resistant surface.

Because some parts of the metal housing were out-of-round, especially near the large diameter, the thickness of the lining varied from approximately 1/4 inch near the flanges to 1/2 inch at points midway between the flanges. After the liner had been returned to the Cleveland laboratory, it was examined and a crack was noted in the ceramic lining that evidently had formed in transit.

An unlined test chamber of similar dimensions was also investigated. Eight alumel-chromel thermocouples were spot-welded on the outside surface of the test chamber in the same positions as those installed on the ceramic-lined test chamber (fig. 3).

## PROCEDURE

Ten thermal shock runs were made, which consisted of operation of the test chamber at a given fuel-air ratio until temperature was constant for 30 minutes. At the end of this time, the fuel flow was abruptly stopped in order that the ensuing blast of cold air would subject the shell to dynamic thermal stresses. These thermal-shock runs were conducted at a low fuel-air ratio, 0.016, and at an air-flow rate of 116 pounds per minute. The average reference outlet-gas temperature during these runs was 1600° F. A thermal shock was also provided after each run by normal shutdown procedure for thermal-shock runs.

An endurance study was conducted at reference outlet-gas temperatures of 2000°, 2400°, 2600° F for 12, 13, $28\frac{1}{2}$ hours, respectively; an inspection of the lining was made after each 6-hour period. The maximum reference outlet-gas temperature of 2600° F was chosen because previous experience had indicated that this temperature was the maximum continuous operating temperature that the thermocouple could withstand without failure from overheating.

The unit was finally operated at increasingly richer fuel-air ratios. All gas-temperature theromcouples were removed for this series because previous runs at a fuel-air ratio of 0.034 and an air-flow rate of 120 pounds per minute had destroyed a shielded alumel-chromel thermocouple by melting and corrosion. Supplementary water sprays were added to the exhaust gas in the reference thermocouple section in order to keep the exhaust-trench gas temperature below its rated value of 200° F.

Chipping tests of the ceramic lining were conducted to determine 814
the degree of adherence of the lining to the housing. A 1/2-pound ball-peen hammer was used, a vigorous blow was directed on the lining, and the resultant cracking or crumbling was noted.

During all runs, the outside metal-shell temperatures were recorded and checked for correlation against fuel- and air-flow measurements in order to aid in obtaining consistent temperature conditions within the burner.

The unlined test chamber was operated at fuel-air ratios of 0.016 and 0.050 with air flows of 116 and 75 pounds per minute, respectively. Outside surface temperatures were recorded for comparison purposes.

## RESULTS AND DISCUSSION

A log of operating times is given in table I. Temperatures measured at several depths in the ceramic lining are presented in table II. The temperature data were plotted against the depth of the thermocouples in the ceramic lining in order to establish the temperature gradient through the lining. (See fig. 5.) These temperatures ranged from 300° F at the surface next to the shell to 1250° F at a point 3/16 inch from the inner surface. Because the locations of the bare metal of the thermocouples could not be determined with great accuracy, the abscissa values shown in figure 5 are not to be considered correct to more than ±1/32 inch. These curves were extrapolated and the temperature gradients were then estimated from figure 5. The average gradient at a fuel-air ratio of 0.050 and an air flow of 75 pounds per minute was 850° F per inch; at a fuel-air ratio of 0.016 and an air flow of 116 pounds per minute, the average gradient was 470° F per inch. These temperatures and gradients are indicative of the approximate operating conditions only of the ceramic lining.

The ceramic lining cracked in a number of places early in the first group of runs. This behavior is in accordance with previous experience with other large pieces of ceramic material. The pieces resulting from the cracks, however, did not fall out; therefore a continuous ceramic shell was preserved at all times.

The reason for the coherence of the ceramic pieces lies in the choice of ceramic material. The particular material used expands after firing, thus setting up compressive stresses in the ceramic shell. These compressive forces keystone the pieces in place. The compressive stress in the ceramic lining was maintained in the axial as well as the circumferential direction because of the constraint inherent in the shape of the liner. The diminished cross section of the chamber at each end of the liner prevented free expansion of the lining in an axial direction.

The compressive stresses in the lining served not only to wedge the pieces together, but also to reduce the extent of cracking. Ceramic materials are notably stronger in compression than in tension. An example is the case of $Al_2O_3$, which manifests a compressive strength of 412,000 pounds per square inch and a tensile strength of 36,000 pounds per square inch. The stresses imposed by thermal gradients alone are, in general, compressive at the inner surface and tensile at the outer surface by reason of the high thermal gradient across a thermal insulator, such as a ceramic material. When these stresses are superposed on the compressive stresses induced by expansion of the ceramic material on setting, the resultant tensile stresses are reduced and compressive stresses increased. This stress distribution favors the poor resistance to tensile failure, with the result that higher thermal gradients may be supported than when the lining is not in compression.

As the gas temperature inside the test chamber is increased, both the ceramic lining and the metal shell expand. Ceramic materials, in general, possess lower coefficients of thermal expansion than those of metals. If the ceramic coating is very thin, the temperatures of the metal shell and the lining will not differ greatly and stresses will tend to be relieved. If the lining is thick, greater than 1/32 inch, the metal temperature will be so much lower than the average temperature of the ceramic that the ceramic will expand more despite its lower coefficient of thermal expansion and the compressive stresses will be increased. The thermal coefficient of linear expansion of the ceramic material was not known, but it is believed to be within the limits of $11 \times 10^{-6}$ and $8.5 \times 10^{-6}$ inches per inch per $^{\circ}C$. The thermal coefficient of linear expansion of the metal was $13.3 \times 10^{-6}$ inches per inch per $^{\circ}C$.

These coefficients of expansion indicate that as long as the ceramic increases in temperature at a rate in excess of about 1.2 times the rate of increase in temperature of the metal, the compressive stress will become greater. If the rise in temperature of the ceramic material is less than this amount, the compressive stresses will tend to be relieved. No gas flow ordinarily takes place through the cracks in the ceramic lining because there is no outlet for this gas. The exception to this statement was the actual failure, which was abetted by a flow of gas through the crack in the lining and out through the interstice between two flanges of the metal shell.

Chipping tests conducted with a ball-peen hammer before and after operation indicated that the lining could withstand considerable mechanical shock without apparent injury. This fact was verified when the test chamber was accidentally dropped 3 feet onto a concrete floor without damage. A vigorous blow with the hammer was required to dislodge any pieces of the lining, even after fracture of the lining.

An unlined test chamber was also operated in order to determine the efficacy of the ceramic material for temperature reduction of the metal shell. Table III shows that the unlined chambers in general appear to run from 200° to 400° F hotter than the shell of the lined chamber at a fuel-air ratio of 0.016 and an air-flow rate of 116 pounds per minute; at a fuel-air ratio of 0.050 and an air-flow rate of 75 pounds per minute, a temperature difference varying from about 200° to about 800° is noted.

## CONCLUSIONS

A ceramic-lined combustion chamber for gas-turbine use was operated at fuel-air ratios up to 0.050. An analysis of the behavior and the mechanism of failure of the ceramic lining under combustion led to the following conclusions:

1. A ceramic coating consisting of common ceramic materials of 1/4-inch to 1/2-inch thickness appears to be suitable for effecting a considerable temperature reduction in the wall temperatures of combustion chambers. In this investigation, temperature reductions of 200° to 400° F were obtained by the use of such a lining at a fuel-air ratio of 0.016 and an air flow of 116 pounds per minute. Reduction of 200° to 800° F were obtained at a fuel-air ratio of 0.050 and an air flow of 75 pounds per minute.

2. A ceramic lining that expands on setting is desirable in order to minimize the cracking caused by thermal gradients and to prevent the total destruction of the lining by preventing the ceramic pieces from falling apart.

3. For combustors of the type investigated, the ceramic lining may be expected to fail chiefly by cracking caused by thermal stresses at temperatures below the softening point of the ceramic material.

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## REFERENCE

1. Harrison, W. N., Moore, D. G., and Richmond, J. C.: Review of an Investigation of Ceramic Coatings for Metallic Turbine Parts and Other High-Temperature Applications. NACA TN No. 1186, 1947.

TABLE I - LOG OF OPERATING TIME

| Run | Time of run (hr) | Total time (hr) | Fuel-air ratio | Air flow (lb/min) | Type of run |
|---|---|---|---|---|---|
| 1 | 0.50 | 0.50 | 0.016 | 116 | Thermal shock |
| 2 | .50 | 1.00 | .016 | 116 | Do. |
| 3 | .50 | 1.50 | .016 | 116 | Do. |
| 4 | .50 | 2.00 | .016 | 116 | Do. |
| 5 | .50 | 2.50 | .016 | 116 | Do. |
| 6 | .50 | 3.00 | .016 | 116 | Do. |
| 7 | .50 | 3.50 | .016 | 116 | Do. |
| 8 | .50 | 4.00 | .016 | 116 | Do. |
| 9 | .50 | 4.50 | .016 | 116 | Do. |
| 10 | .50 | 5.00 | .016 | 116 | Do. |
| 11 | 7.25 | 12.25 | .021 | 100 | Preliminary endurance |
| 12 | 2.58 | 14.83 | .021 | 110 | Do. |
| 13 | 4.25 | 19.08 | .034 | 120 | Do. |
| 14 | 5.16 | 24.25 | .040 | 85 | Do. |
| 15 | 6.00 | 30.25 | .018 | 110 | Thermal endurance |
| 16 | 6.00 | 36.25 | .018 | 110 | Do. |
| 17 | 6.00 | 42.25 | .021 | 110 | Do. |
| 18 | 7.00 | 49.25 | .021 | 110 | Do. |
| 19 | 6.50 | 55.75 | .023 | 110 | Do. |
| 20 | 6.00 | 61.75 | .023 | 110 | Do. |
| 21 | 6.00 | 67.75 | .023 | 110 | Do. |
| 22 | 4.00 | 71.75 | .023 | 110 | Do. |
| 23 | 6.00 | 77.75 | .023 | 110 | Do. |
| 24 | .50 | 78.25 | .010 | 150 | Temperature survey |
| 25 | 2.50 | 80.75 | .012 | 140 | Do. |
| 26 | 4.00 | 84.75 | .016 | 130 | Do. |
| 27 | 3.50 | 88.25 | .012 | 100 | Do. |
| 28 | 3.00 | 91.25 | .012 | 50 | Do. |
| 29 | 7.00 | 98.25 | .016 | 110 | Do. |
| 30 | 5.00 | 103.25 | .019 | 110 | Do. |
| 31 | 3.50 | 106.75 | .016 | 116 | Do. |
| 32 | 1.25 | 108.00 | .025 | 110 | Do. |
| 33 | 3.50 | 111.50 | .030 | 110 | Do. |
| 34 | 5.00 | 116.50 | .030 | 110 | Do. |
| 35 | 4.00 | 120.50 | .030 | 120 | Do. |
| 36 | 6.00 | 126.50 | .030 | 120 | Do. |
| 37 | 2.00 | 128.50 | .030 | 85 | Do. |
| 38 | 2.00 | 130.50 | .035 | 120 | Do. |
| 39 | .50 | 131.00 | .050 | 75 | Do. |
| 40 | .67 | 131.67 | .050 | 75 | Do. |
| 41 | .67 | 132.35 | .050 | 75 | Do. |

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TABLE II - TEMPERATURES MEASURED AT SEVERAL DEPTHS

IN CERAMIC LINING

| Indicated temperature, °F | | | | | | Air flow (lb/min) | Fuel-air ratio |
|---|---|---|---|---|---|---|---|
| Center section | | | | Rear section | | | |
| [a]Top | Side | Bottom | Side | Top | Bottom | | |
| 670 | 555 | 785 | 435 | 385 | 273 | 116 | 0.016 |
| 1115 | 1145 | 1195 | 900 | 790 | 690 | 75 | .050 |

TABLE III - COMPARISON OF OUTSIDE SHELL TEMPERATURES

FOR LINED AND UNLINED COMBUSTION CHAMBERS

| | Indicated temperature, °F | | | | | | Air flow (lb/min) | Fuel-air ratio |
|---|---|---|---|---|---|---|---|---|
| | Center section | | | Rear section | | | | |
| | Top | Side | Bottom | Side | Top | Bottom | | |
| Ceramic-lined chamber | 520 | 510 | 405 | 290 | 365 | 250 | 116 | 0.016 |
| Unlined chamber | 880 | 940 | 635 | 1130 | 600 | 715 | 116 | 0.016 |
| Ceramic-lined chamber | 1055 | [a]825 | 920 | 660 | 775 | 625 | 75 | 0.050 |
| Unlined chamber | 1390 | 1385 | 1135 | 1455 | 1290 | 1420 | 75 | 0.050 |

[a]Estimated value, obtained from one reading before thermocouple failed.

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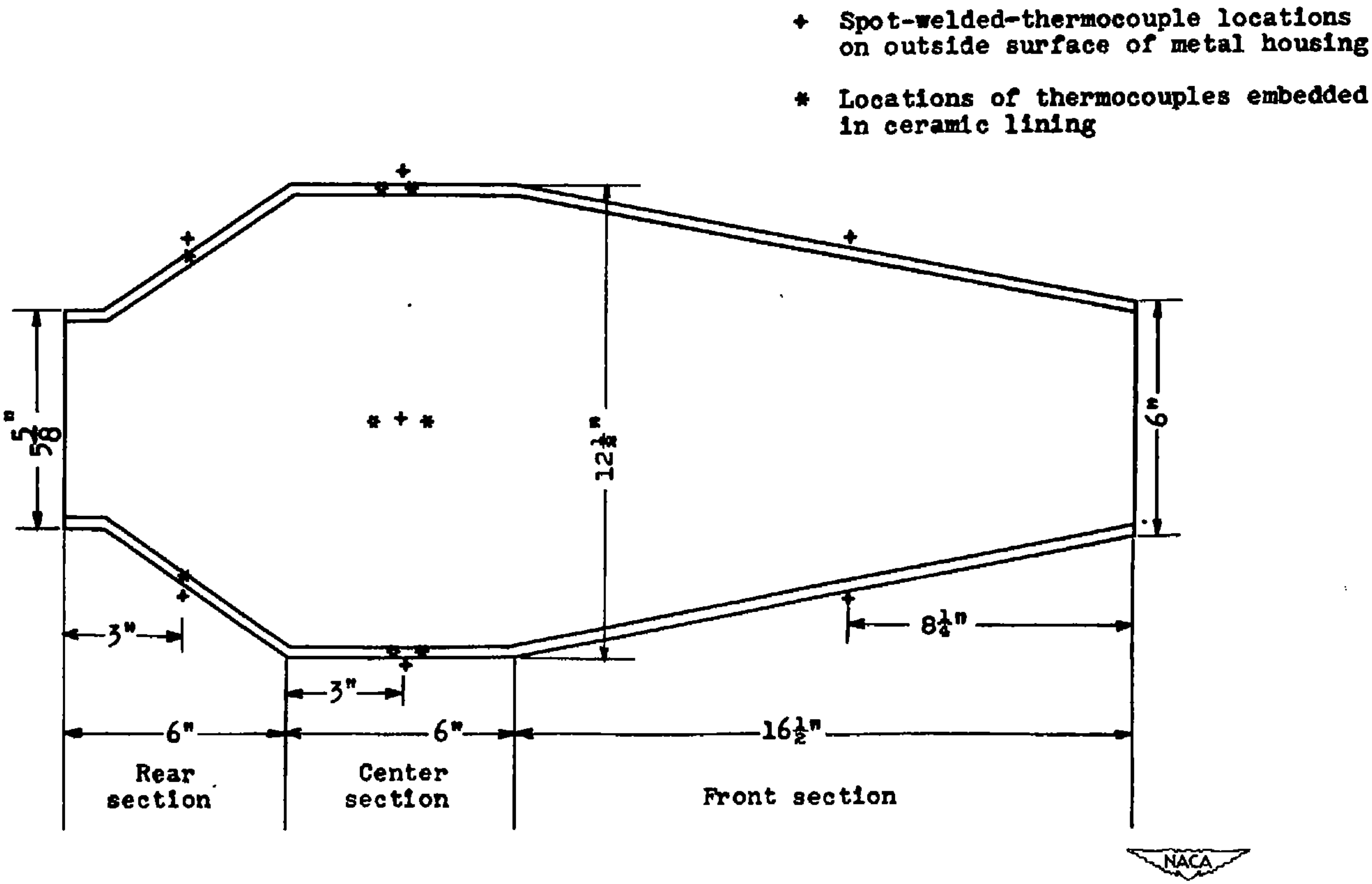


Figure 1. - Sketch showing location of thermocouples installed on outside surface of metal housing and embedded in ceramic lining and dimensions of test chamber.

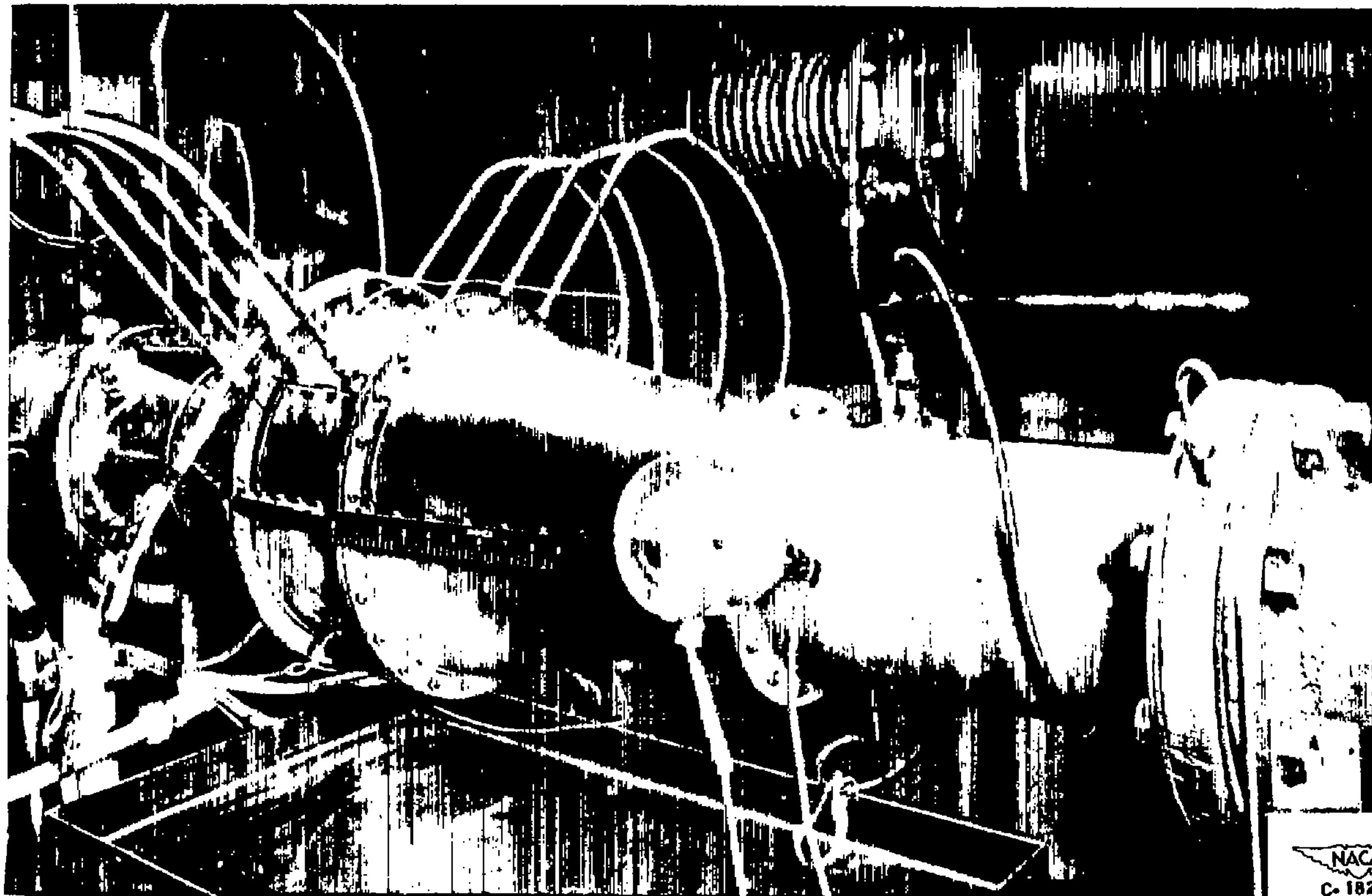

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Figure 2. - Photograph of test unit. Air-flow direction from right to left.

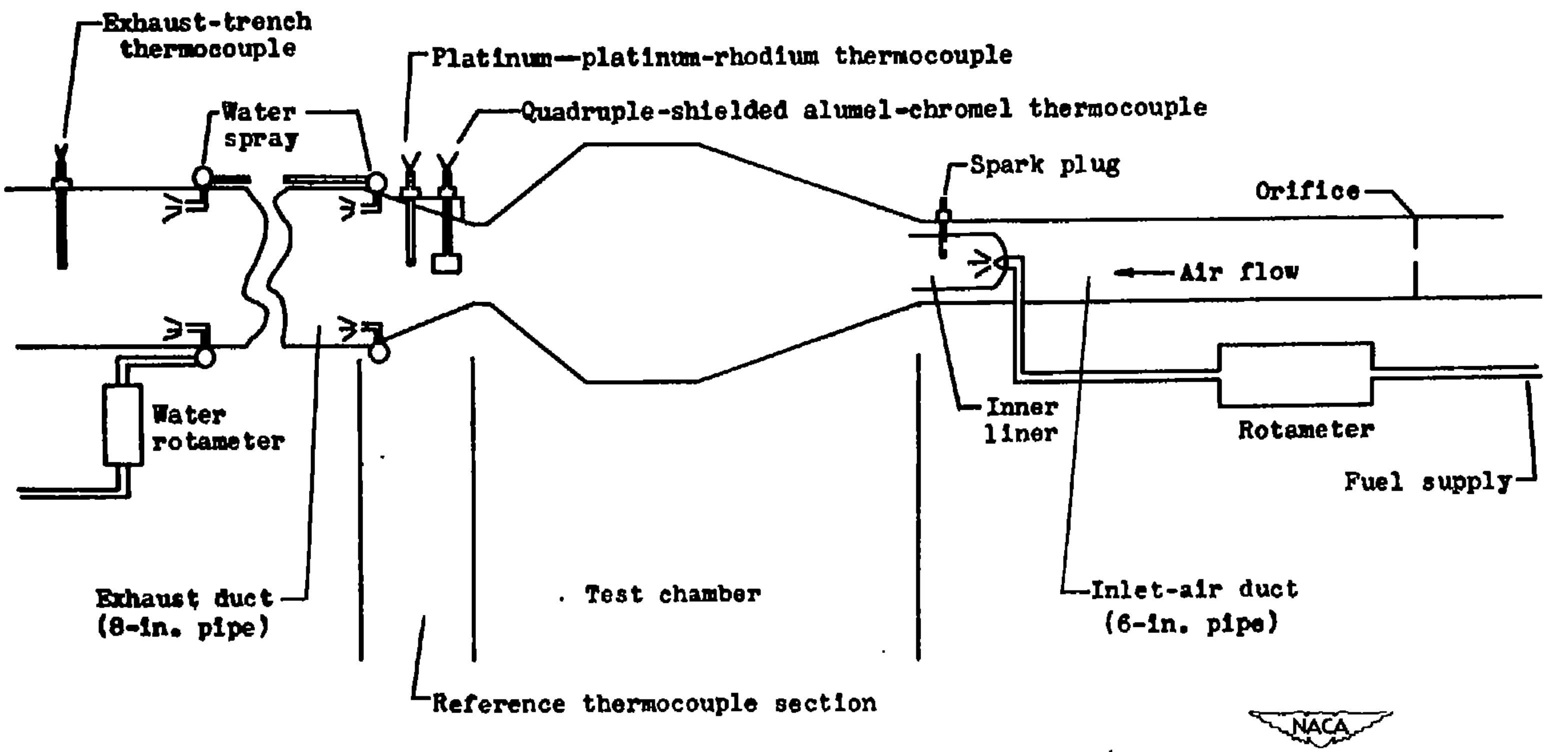


Figure 3. - Schematic diagram of ceramic-lined combustion-chamber test unit.

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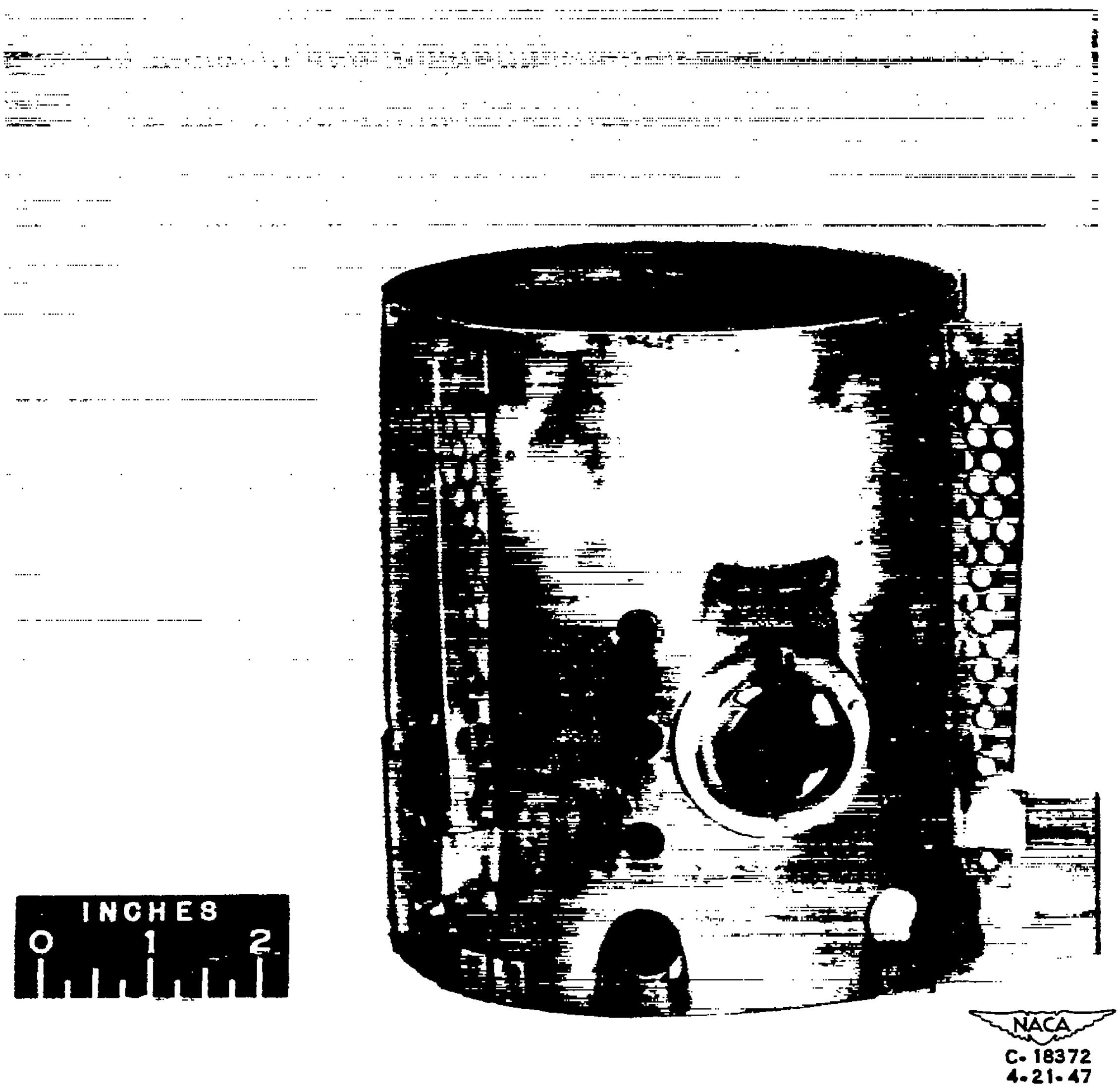


Figure 4. - Inner liner used in test unit.

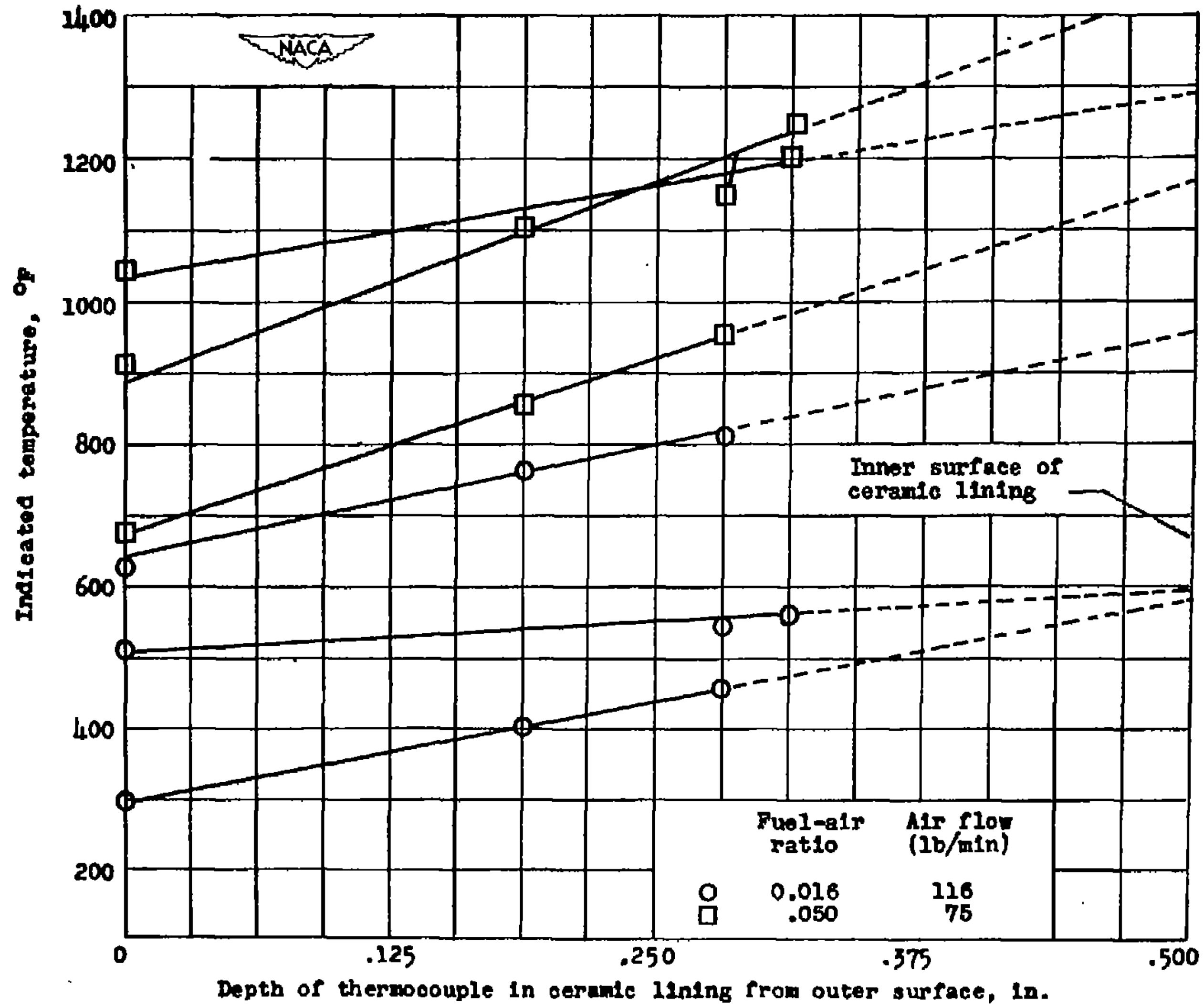


Figure 5. - Temperature gradient through ceramic lining for two fuel-air ratios and air flows.